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IMPROVED DAYLIGHT COMFORT BY A NEW 3D-FOIL THAT ALLOWS TO TRADE OFF SOLAR GAINS AND LIGHT INDIVIDUALLY

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Summary. *This paper presents a new shading approach for ETFE-membrane cushions. Due to the high visible transmission of an ETFE-foil (one layer transparent ETFE foil ≈ 92% @ 200µm) the risk of overheating and glare effect in the summer is very high. Therefore, a new angle-selective shading system blocks off direct sunlight but diffuse sunlight can enter the building. Especially, this measure means a reduction of the cooling energy loads and should improve the thermal- and visual comfort. In this paper we focus on the visual comfort of the daylight factor, brightness and glare effect through the new 3D-foil.*

1 INTRODUCTION

From an energy perspective, transparent membrane constructions with a U-value of about 2.1 W/m²K (@ three-layer construction) [1, pp. 216] will always act as a heat sink compared to opaque exterior walls or roofs with a U-value of about ≈ 0.28 / 0.20 W/m²K [2] due to the worse thermal transmission coefficients (U-value). Therefore, the heating energy demand will be increased by reducing the solar gains. But on the other hand, the high visible transmission of membrane construction leads to a high utilization of the incoming daylight and reduces artificial lighting inside the building. Otherwise the risk of overheating without an appropriate sun protection by increased solar gains in summer is very high. Typical materials for transparent membrane constructions are ethylene-tetra-fluoro-ethylene (ETFE). ETFE does not become brittle or yellowed because it absorbs a minimum amount of the UV-radiation and has a self-cleaning effect [1, pp.97]. These properties allow for long lasting applications.

ETFE-foils can be printed (fritting) with different printing patterns (e.g. points) and colors (optimal colors have a high reflection capacity). Furthermore tinted ETFE material can be used in several colors. Thereby the optical properties (transmittance [τ], reflectance [ρ] and the absorption [α] coefficients) can be controlled by the pigmentation grades and printing patterns. The current sun protection solutions are summarized in [5].

The main disadvantage of current state-of-the-art shading solutions for foils is the constant transmittance and reflection coefficient regardless of the incidence angle of the sun.

However, if a sun protection is used the natural daylight in the room will be decreased. Nevertheless sufficient illumination through daylight without glare phenomena needs to be ensured in order to reduce the energy consumption for artificial lighting. Visible light consists of electromagnetic radiation which can be perceived by the human eye. The visual range (T_{vis}) is in the wavelength range of between approx. 380 and 780 nanometers (nm) [1, pp.113]. When using transparent ETFE-foils the high visual transmission can often cause glare phenomena, according to [4]. Glare can be caused by the contrast of light and dark surfaces or by direct and/or indirect reflections. Thereby, the luminance distribution describes the brightness impression of a surface thus high luminance should be avoided, because glare can occur. Uniform contrast relation should prevail, because too high contrast can lead to fatigue and too low luminance contrasts may make the work or lounge area unattractive. [3]

To avoid some of the above mentioned daylight problems, the design of the shopping mall "Dolce Vita Tejo" in Lisbon (Amadora) has been inspired by the widely use of the architectural idea of a shed roof (saw-tooth roof), see Figure 1. The aim was an optimal use of daylight with good thermal comfort inside the building. This was achieved by printing the foil-layers, with partly double printed ETFE-foils.

Through the roof shape and the foil-printing it is possible to let diffuse sunlight enter the building from the northern part of the cushion surface equipped with a transparent ETFE-foil and block off direct sunlight from the southern part of the cushion surface thought out the printing. The membrane cushions are installed as an overhead roof system with dimensions of each membrane cushion of approx. 10 m x 10 m [1, pp.256].

Figure 1: Shopping mall: Dolce Vita Tejo in Lisbon. Source: Hannes Marx

The shading approach discussed here is similar to the project "Dolce Vita Tejo" and is also inspired by a shed roof structure. However, the saw-tooth structure is downsized to a millimeter scale (3D-Foil). Compared to the membrane cushions in "Dolce Vita Tejo" the working model of the new shading approach is much smaller, the scale factor is about 500, see Figure 2. This requires a special modification of the applied ETFE-foil. The foil will not only be printed but also additionally spatially transformed, so that the printing pattern can be adjusted in the design phase considering the sun position and the direct sunlight radiation.

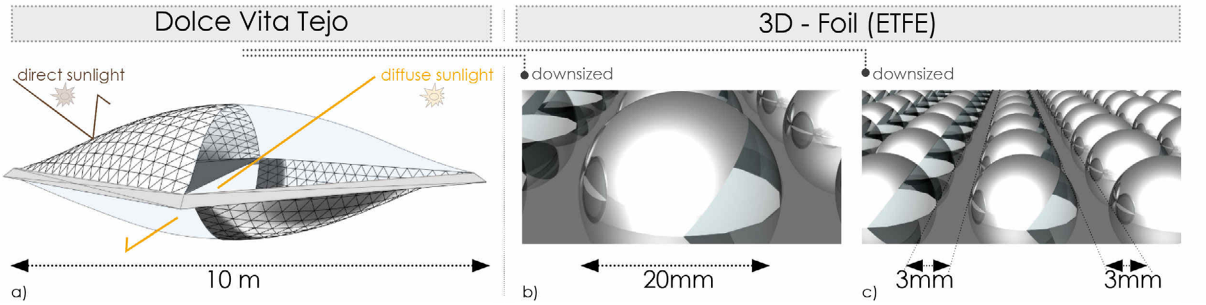


Figure 2: a) "Dolce Vita Tejo" in Lisbon, b) c) hemisphere geometry of the new shading approach: downsized to a millimeter scale (r = 10mm)

In this paper we focus on the visual comfort (daylight factor and glare phenomena) by using a fixed geometry (hemisphere: radius = 10 mm) with optimized printing pattern for Stuttgart, Germany. In [5] and [7] we describe the thermal simulation method with TRNSYS 17 because it's a special requirement to represent the small structure for the energy loads (cooling and heating).

1.1 3D – Foil (form optimization and material samples)

The hemisphere geometry is the best option for the new spatially transformed shading approach, because the significant benefits compared with location- and orientation specific geometries are too expensive in the manufacturing for the tooling. Therefore, only the printing part on the hemisphere can exactly be adjusted to the sun position by each project. Consequently, a hemisphere can be applied for both, façades- and roofs.

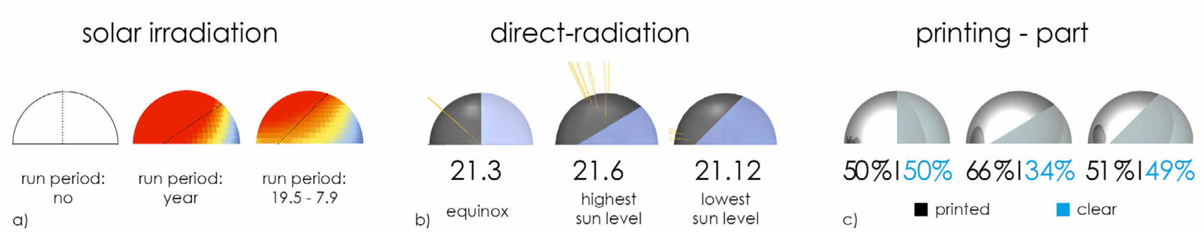


Figure 3: Printing optimization: hemisphere
a) solar irradiation (run period) b) direct-radiation (sun position) c) printing part

In order to achieve the ideal printing pattern, different influencing factors have to be analyzed:
intensity of the solar irradiation [kWh/m²], sun position (direct radiation), sun hours as well as time limits to guarantee solar gains in the winter case (Stuttgart: 8th Sept. to 20th May).
In [7] the thermal simulations of the total energy load (cooling/heating) are presented for different geometries (saw-tooth structure, pyramid, hemispheres) and different printing patterns. The results show a considerable reduction of the solar gains in the winter months (comparing the variants) and thus indicate a higher total energy loads for some geometries. These results are essential for the sun protection solution, which have an optimal printing pattern for Stuttgart with 51%, see Figure 3c. An optimal printing pattern improves the

thermal comfort, saves cooling energy because the direct radiation is blocked off and solar gains in the winter month can enter the room. Furthermore, it is intended to generate a glare- and shadow free situation with sufficient daylight by diffuse radiation.
The new spatially transformed foils are installed in the middle-layer of a membrane cushion. The building integration of the new spatially transformed foil is described in [5] in more detail.

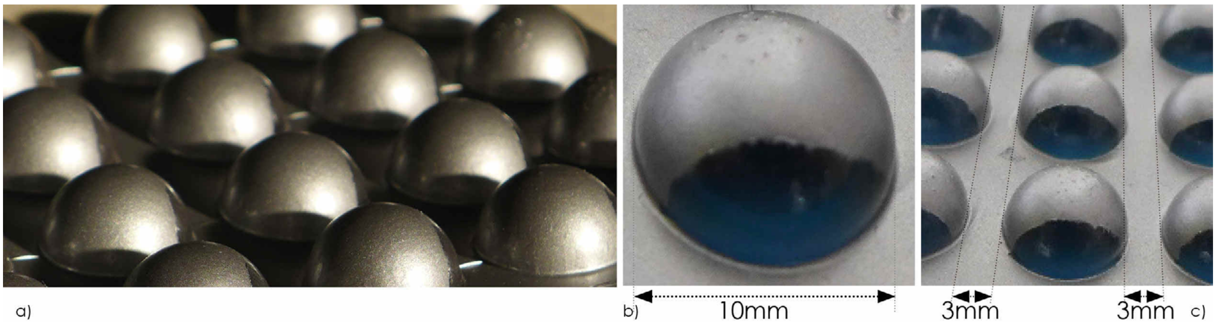


Figure 4: Material samples spatially transformed: 3D – Foil, optical impression

First material samples are made of PVC (polyvinyl chloride) in lab-scale 1:1 in the university´s workshops with a thickness of 200 µm regarding the producible and optical impression, see in Figure 4. Based on the previous findings and results prototypes with the dimension of 700 x 700 mm are currently produced. These prototypes will then be measured to gather angle-dependent measurement data for the transmission [τ], reflection [ρ] and total energy transmittance (g-value) and finally they will be used for demonstration as well.

2 SIMULATION METHOD

First of all, the light foundations are based on the spectral data of transparent and nearly 100% printed ETFE-foil with a thickness of 200 µm. This is required to calculate new materials for the material list [rad-file] to use it in DIVA 3.0 (Radiance), see Table 1.

Table 1: Material input for DIVA: ETFE-foil

Window *Description*	**color** *red/green/blue*	**specularity** *[-]*	**roughness** *[-]*	**transmission** *[-]*	**transmitted** *specularity*
ETFE - clear	0.98	0.08	0.00	0.99	0.98
ETFE – printed	0.44	0.29	0.00	0.16	0.40

Then a fictitious 3D-building model (Figure 5) was built in Rhino to simulate the illuminance [cd/m²], brightness impression and daylight factor (DF) with the aid of dynamic simulation in DIVA 3.0. Two different variants were created for this study, one for the visual comfort (intensity of daylight) and another for the daylight factor (sufficient natural daylight). The basic simulation model is a three-layer membrane cushion with 2 air chambers in which the sun protection (i.e. the spatially transformed 3D-foil with hemisphere geometry) is installed (cf. Figure 5a).

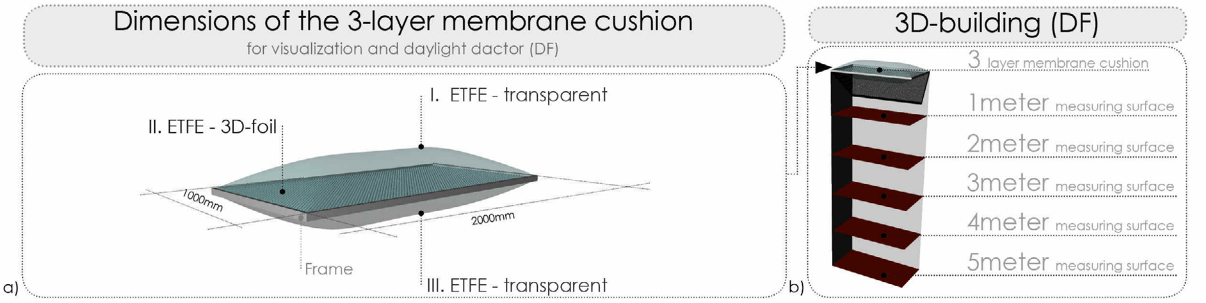


Figure 5: 3D simulation model:
a) three-layer membrane cushion (1000 x 2000 mm, high: 500 mm) c) sufficent daylight factor (DF) dependent of height.

3 RESULTS AND DISCUSSION

In the following simulations the spatially transformed sun protection (hemisphere geometry) with a radius of 10 mm and distance to each geometry of 3 mm cf. Figure 2c, will be compared within the membrane system with a conventional horizontal printed ETFE-foil (without spatially transformation). Furthermore, the identical printing part is analyzed in more detail with respect to the incoming of the daylight factor (DF) and glare phenomenon by using false colors (cd/m²) as well as the contrast differences and impact of shadow incidence. Only a small part of the 3D – foil (1000 x 2000 mm) is considered because through the small structure, the simulation time for a large area takes too long. In a next step, the prototypes can be measured in the artificial sun at the university´s workshops to analyse the daylight factor (DF).

3.1 Visual comfort

Figure 6 depicts the results for the 21st of June at 1pm with direct radiation. The 21st of June is the day with the highest sun position at 13:25 am (azimuth: 179.49°, zenith: 64.66°) in Stuttgart cf. Figure 3b. Comparing the visualization of the spatially transformed 3D-foil and the conventional horizontal printed foil, both variants are distinguishable regarding the brightness.

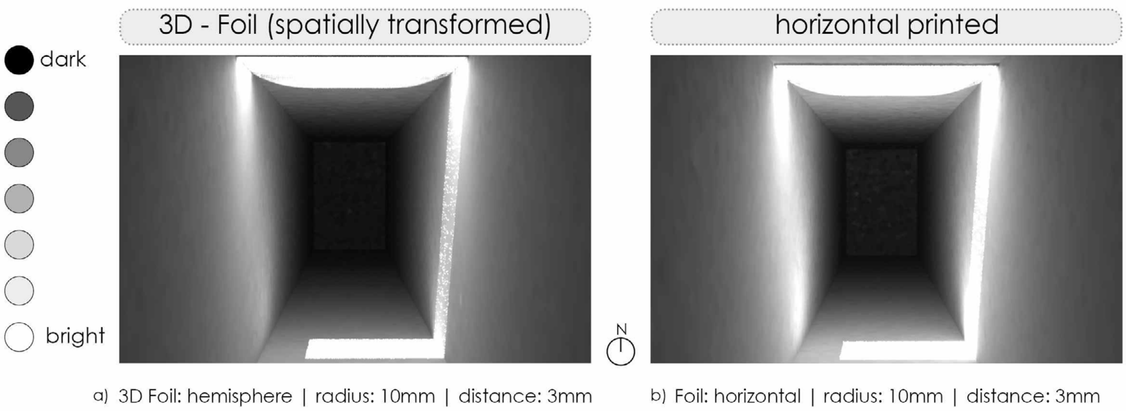


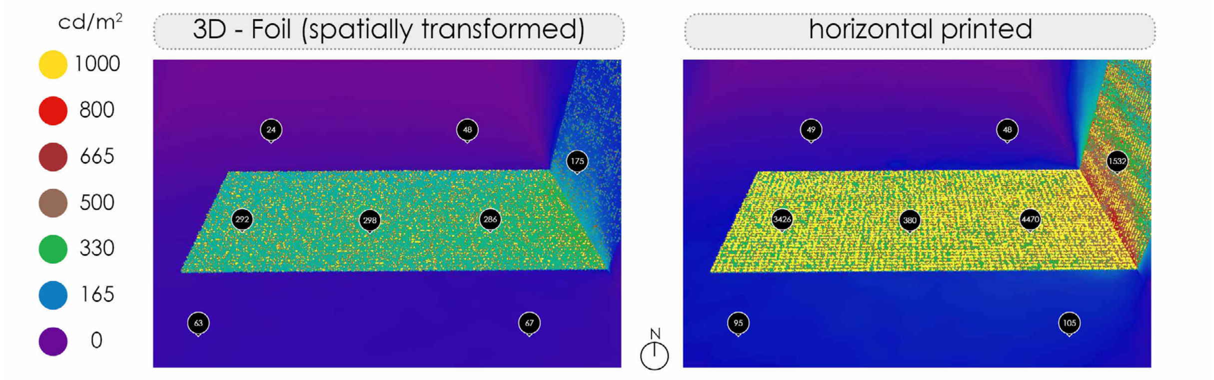
Figure 6: Visualization in DIVA: brightness impression, view from the south side.
a) 3D-Foil b) conventional horizontal printed

The visualizations in Figure 6 show the benefits of the new spatially transformed ETFE-foil regarding the impact shadow and brightness impression. The direct sunlight is blocked off and leads to less reflection glare inside the room. The further reflection properties of the components are listed in Table 2.

Table 2: Material (reflecion properties)

Input materials	Material name (DIVA)	Description
wall, floor, celling	GenericInteriorWall	50% reflectance
Frame	metal diffuse	50% reflectance

A clear sky with sun has a calculated illuminance of about 25.000 cd/m² (based on the climate data by the German Meteorological Service, Stuttgart). Figure 7 shows a false-color illustration and analyzes illuminance of the direct incidence of sunlight on the floor and a small part of the wall.
The achieved illumination requirements for a good comfort such as for a workplace (technical drawing) are an illuminance of 750 cd/m²; a color inspection of 1000 cd/m² and painting of 1000 cd/m² [3].



a) 3D Foil: hemisphere | radius: 10mm | distance: 3mm b) Foil: horizontal | radius: 10mm | distance: 3mm

Figure 7: False-color
a) 3D – ETFE- Foil b) horizontal ETFE-foil

Figure 7a (3D-foil) shows the highest illuminance with 1774 cd/m² compared to the horizontal printed ETFE-foil where the highest illuminance is at 7302 cd/m². The average of the illuminance on the floor is for the 3D-Foil 528 cd/m² and for the horizontal printed foil at 1981 cd/m² in this viewing angle. This is a reduction of the illuminance (direct sunlight) of about 73%.

3.2 Daylight quality (DF)

The aim of the daylight factor analysis is to show the benefits and risks of the new 3D foil regarding to the natural daylight supply beginning from the floor of the room up to the spatial transformation (3D-Foil). Because of different levels of direct sunlight blocking partly 100%

due to the adjusted printing pattern, different variants were used. The daylight factor is calculated by diffuse sky conditions, i.e. without direct radiation as follows:

$$DF = (E_p / E_a) * 100 \quad (1)$$

Thereby, the diffuse sky is calculated with 17.900 cd/m². Aimed daylight factors (DF) with rooflights should not be less than $D_{min} < 2\%$. Regarding the overheating in the summer the "DF" should not be higher than $D_{max} > 10\%$ for rooms with a limited room height [8].

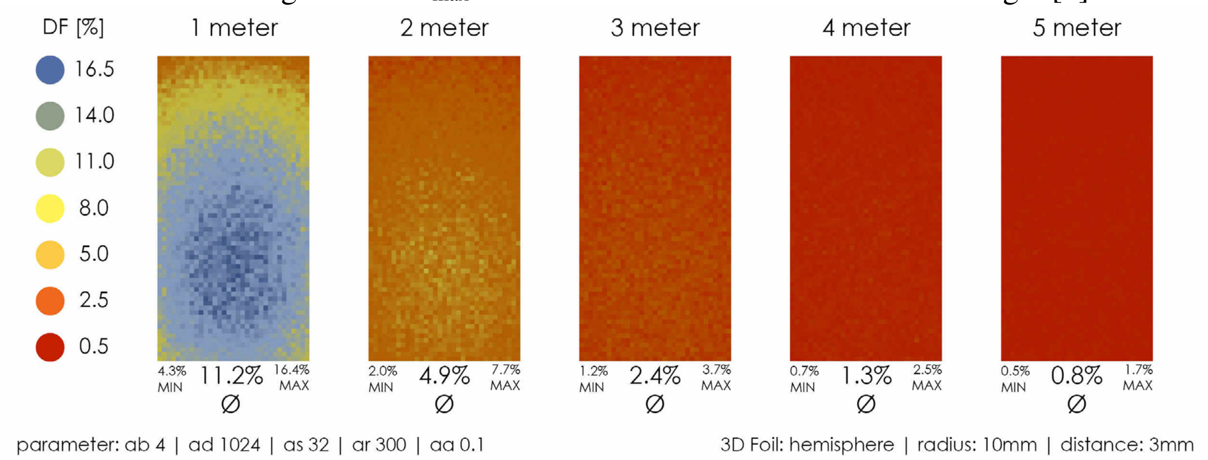


Figure 8: Daylight Factor (DF)

The daylight factor (DF) at a distance of 1 meter from the roof amounts 11.2%, at a distance of 3 meter 2.4% and at a distance of 5 meter it is only 0.8%. Therefore, the "DF" is sufficient up to a distance between of 3 and 4 meter.

Another criterion for the daylight conditions is the uniformity [G] of the daylight factor:

$$G = (D_{min} / D_{max}) \quad (2)$$

A ratio from 1:4 is very good, but in case of G < 1:10 the uniformity is described as insufficient [8]. At a distance of 4 meters the minimum "DF" (D_{min}) is 0.7% and the maximum is (D_{max}) is 2.5% this is a uniformity [G] of 1:3,6.

Compared with a horizontal printed ETFE-foil at the distance of 4 meter the "DF" is also by 1.3%, D_{min} = 0.7% and D_{max} =2.3%.

4 CONCLUSION & OUTLOOK

This paper is a short evaluation of the new shading approach for membrane structures. The general problem is the fixed transmission- and reflexion coefficient for conventional ETFE sun protection. This is addressed by the new spatially transformed ETFE-foil (3D-foil). Thereby, the idea of the shed roof (saw-tooth structure) is downsized to a millimetre scale. However, the new shading approach is installed in the middle of a multi-layer membrane cushion. An optimal geometry is a hemisphere, because the printing pattern can be adjusted exactly to the sun position independently from the spatial transforming process. In this paper the new sun protection is analyzed for Stuttgart (Germany) with an optimal printing pattern of about 51%. This allows for a reduction of the cooling energy loads of about 69% according to a thermal simulation with TRNSYS 17 compared to a horizontal printed ETFE-foil [7]. A sufficient daylight factor (DF) allows from about 2.5 to 1.3% at a distance up to 4 meters. Because of the diffuse sky condition there is no significant difference between the new 3D-foil and a conventional horizontal printed ETFE-foil.

Furthermore, the glare risk can be reduced especially for the direct and reflection glare by the new shading approach. Based on the reduction of the illuminance (direct sunlight) of about 73%, this ensures even an uniform illumination inside the room. Therefore, the essential effect at the new angle-selective shading system for membrane structure is to block off a high amount of the direct sunlight and enter sufficient natural daylight for the thermal and visual comfort. The simulation results (DF) will be validated by measurements of the prototypes in the coming month.

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REFERENCES

[1] Knippers J., Cremers J., Gabler M., Lienhard J., Construction Manual for Polymers and Membranes. Munich: BIRKHÄUSER/ DETAIL, 2011. p. 216.

[2] Verordnung über energiesparenden Wärmeschutz und energiesparende Anlagentechnik bei Gebäuden (Energiesparverordnung – EnEV), 24.10.2015. p.30

[3] DIN EN 12464-1: Light and lighting – Lighting of work places – Part 1: Indoor work places; German Version EN 12464-1:2011

[4] Lau B., Masih D., Ademakinwa A., Low S., Chilton J.: Understanding Light in Lightweight Fabric (ETFE Foil) Structures through Field Studies, TensiNet 2016, Newcastle/UK, Procedia Engineering 155; 2016. p. 479 – 485

[5] Cremers J., Marx H.: A new printed and spatial transformed ETFE foil provides shading and improves natural light and thermal comfort for membrane structures, PLEA 2017, Edinburgh/UK.

[6] Cremers J., Marx H.: Comparative Study of a New IR-Absorbing Film to Improve Solar Shading and Thermal Comfort for ETFE Structures, Procedia Engineering 155 (2016) 113-120.

[7] Cremers J., Marx H.: 3D-ETFE: Development and evaluation of a new printed and spatially transformed foil improving shading, light quality, thermal comfort and energy demand for membrane structures, CISBAT 2017, Lausanne/CH (currently still unpublished).

[8] DIN EN 5034-6: Daylight in interiors – Part 6: Simplified determination of suitable dimensions for rooflights; German Version: 2007